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Recent Progress on the ATHENA Positron Accumulator

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Abstract. The Positron Accumulator for the ATHENA anti-hydrogen experiment at CERN, Geneva has recently been upgraded with a new 50 mCi ^{22}Na β^{+}-radioactive source. Following this, rapid progress has been made in optimizing and characterizing the properties of the positron plasma. The rotating wall technique has also been implemented in the accumulation region and has been shown to lead to compression of better than a factor of 10 in density and markedly increased lifetimes, even when using the N_2 buffer gas as a cooling gas. Using these techniques we have routinely accumulated up to 2×10^8 positrons in a few minutes. The positron plasma has a FWHM of only 3-4 mm when using the rotating wall which compares with a FWHM of 15 mm without the rotating wall.

INTRODUCTION

The ATHENA anti-hydrogen experiment at CERN, Geneva aims to produce and trap anti-hydrogen for further studies including tests of CPT and the weak equivalence principle [1-5]. In such a quest to synthesize atomic low-energy anti-hydrogen there are many parameters to optimize. A few of these have to do with maximizing the number, density and lifetime of the constituent particles of positrons and anti-protons. In order to accumulate as many positrons as possible a positron accumulator based on the design of the Surko Group at the University of California San Diego [6-8] has been constructed over the past few years. In this accumulator we have trapped up to 2×10^8 positrons prior to transferring them across a low field region to the main ATHENA recombination trap situated inside a 3 T magnetic field.

EXPERIMENTAL

The positron accumulator traps and cools a continuous beam of slow positrons. The slow positrons injected into the accumulator are generated by moderating β+ particles from a ^{22}Na radioactive source and guiding them into the trapping region using a

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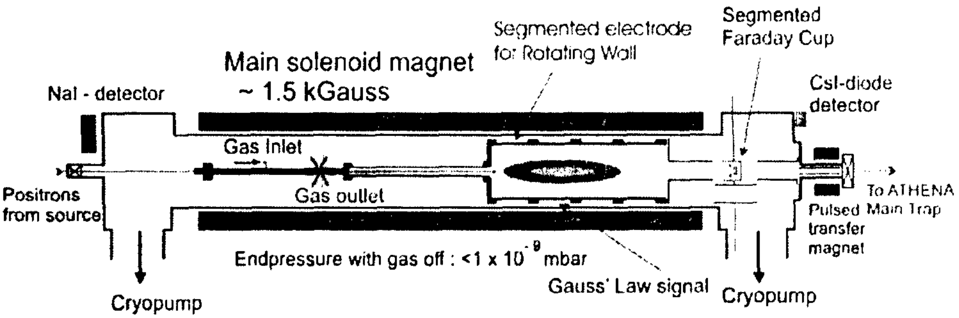

Figure 1. Schematic overview of the ATHENA Positron Accumulator, showing the electrodes used for the rotating wall and the electrode used to generate the Gauss' Law signal.

magnetic field. Recently the ATHENA Positron Accumulator has been fitted with a new 50 mCi ^{22}Na source from NAC in Cape Town, South Africa. A cryogenic cold head capable of reaching 5.5 K cools down the source and makes it possible to grow a solid neon moderator directly on the source. The new source has meant that a slight redesign was necessary as the dimensions of the new source are quite different from the old source. Details of the source end design as well as further details of the experimental set-up can be found elsewhere [9, 10]. Placing a NaI-detector close to the gate valve between the source end and the main trapping region made it possible to optimise the moderator growth. During moderator growth this gate valve would be closed and the positrons would annihilate on the closed valve. To calibrate the NaI signal to obtain the absolute beam strength a channeltron detector was briefly inserted here and coincidence measurements performed. The primary positron beam now has an intensity of 7×10^6 positrons per second.

The trapping scheme used is similar to that used in the new positron trap of the Surko Group [6] and utilizes nitrogen buffer gas to trap and cool the positrons. After trapping the axial confinement is provided by applying appropriate electric potentials to the electrode array while the radial confinement is provided by a 0.15 T axial magnetic field.

One of the trapping electrodes (see Fig. 1) is split into 6 segments, making it possible to use it to compress the plasma by applying a rotating electric field ('rotating wall') [11]. This method has been shown recently to work well also for positrons plasmas [12-13]. In our case the electrodes used have a significantly larger radius (~10 cm) than in earlier experiments but recent results have shown that we can still influence the positron plasma from that distance. Using a rotating wall will lead to heating of the plasma and since the magnetic field in our trap is too small to allow re-cooling using synchrotron radiation another means of cooling the plasma has to be present. We have so far used the nitrogen already present in the form of the buffer gas to cool the plasma again. However, it has been shown [13] that nitrogen is not a very efficient choice as cooling gas, so a CF_4 gas line is presently being commissioned. It should be noted though, that all the data presented in this paper were obtained using nitrogen as a cooling gas. Having the rotating wall present in the accumulation trap means that we can use the rotating wall during accumulation and thus try to increase the lifetime of the positrons in the presence of the buffer gas. This in turn should increase the overall number of positrons we can accumulate, which will be very beneficial when trying to make anti-hydrogen.

The detection system used for our experiment consists of 3 detectors: (1) A segmented Faraday cup detector consisting of 9 plates to get information about the size and position of the plasma. The total size of the Faraday cup is 25 cm^2 and it is situated outside the main magnet in a region where the magnetic field is about a quarter of the field inside the trap. This means that the data obtained from the Faraday cups is 'magnified' compared to the actual sizes inside the magnet and to get the true sizes this magnification factor has to be taken into account. (2) A CsI-diode detector to detect the positron annihilation signal. (3) A 'Gauss' Law' signal from one of the confining electrodes caused by charge being induced on the electrode as the confined plasma is being dumped on the Faraday cup. The whole experimental set-up including the data acquisition from the detectors has been automated to make it possible to run the experiment remotely.

After trapping the positrons still need to be transferred to the 3 Tesla ATHENA main magnet where the antiproton capture trap and the recombination trap is situated. A special transfer section has been constructed for this purpose. This section consists of vacuum separation valve, a pumping restriction, a number of transfer electrodes as well as a transfer magnet capable of pulsing from 0 to 1 Tesla in 20 ms and staying at 1 Tesla for 1 s. This system has been installed and undergone preliminary testing.

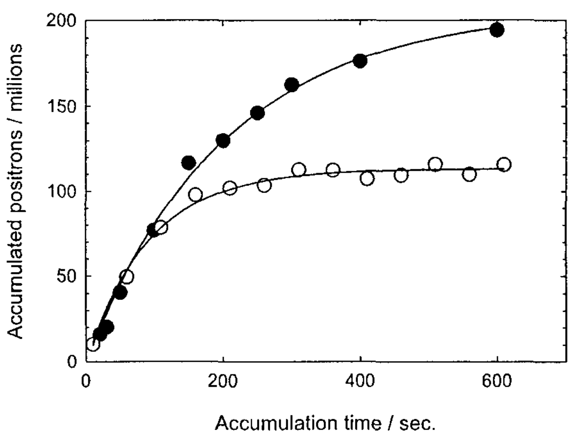

Figure 2. Accumulation of positrons. The open circles show accumulation of positrons without using the rotating wall technique, but with the bottom of the trap lowered by 4 V during the accumulation. The solid circles show accumulation while using the rotating wall technique. The rotating wall was on for the last 50% of the accumulation time. The frequency used was 500 kHz at an amplitude of 0.4 V. In this case the bottom of the trap was lowered by 6 V during accumulation. Using the rotating wall increases the lifetime by almost a factor of 2 while the accumulation rate remains about the same.

However, due to problems with the power supply for the magnet no data on the transfer will be presented in this paper.

RESULTS

Following the installation of the new source rapid progress has been made in optimizing and characterizing the accumulated positron plasma and in implementing the rotating wall technique. This rapid progress was made possible not only by the fact that a larger source means more positrons but also, as we shall see later, that when it is possible to accumulate more than a few tens of million of positrons many of the plasma parameters seem to become more stable. Since most of the data that will be presented here has been obtained recently a thorough analysis of the data has not yet been completed and parts of it are not yet understood in detail.

The increased number of positrons made available by the new source made it possible to optimise the electrode potentials and buffer gas better and also made a fine-tuning of the alignment of the magnetic field to the physical axis of the system possible simply by carefully analysing the data obtained. The better alignment in turn lead to an increase in the total number of positrons trapped since the lifetime of the positrons was increased. Figure 2 shows the end result of this fine-tuning. It was thus possible to accumulate more than 100 million positrons in a few minutes. When using

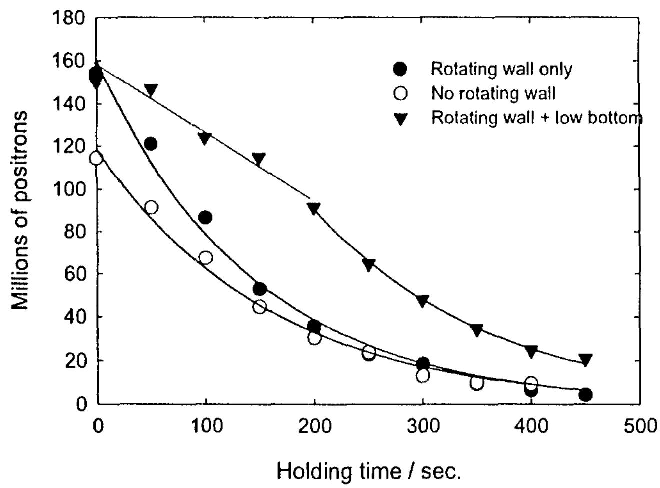

Figure 3. Decay of the positron plasma after the buffer gas is pumped out and the rotating wall is turned off. The frequency used for the rotating wall was 400 kHz and the amplitude used was 0.2 V. The rotating wall was on for the last 50% of the accumulation time. For the data when the rotating wall was used together with lowering of the bottom of the trap during accumulation, the trap bottom was lowered by 4 V.

a suitable (see later) frequency and amplitude for the rotating wall and applying the rotating wall for the last 50 % of the accumulation time it was possible to double the lifetime of the positrons in the presence of the buffer gas while maintaining the same accumulation rate and we therefore now routinely accumulate about 200 million positrons with such settings. The data using the rotating wall shown in Figure 2 yielded a lifetime of 200 seconds when fitted to the standard accumulation formula while the data without the rotating wall gave a lifetime of 95 seconds. It is important to stress that this is with the buffer gas present in the trap. The increase in the lifetime when using the rotating wall shows that under normal operation without using the rotating wall the plasma does not appear to be in the annihilation limit, i.e. the limit where annihilation on the rest gas (buffer gas) is the dominant loss. Rather it would indicate that there is still a large collisional cross-field drift to the electrode walls.

In order to try to accumulate as many positrons as possible we also tried to lower the bottom of the trap gradually during accumulation. This has been shown previously [6] to increase the number of accumulated positrons. However, no increase was found, possibly due to the fact that the trap is not filled to the space charge limit before the bottom is lowered.

Lowering the bottom of the trap gradually during accumulation did turn out to have one surprising effect though. It dramatically increased the lifetime of the positrons after the buffer gas was pumped out. Figure 3 shows the result of such a lifetime measurement. The data for accumulation with and without a rotating wall were both

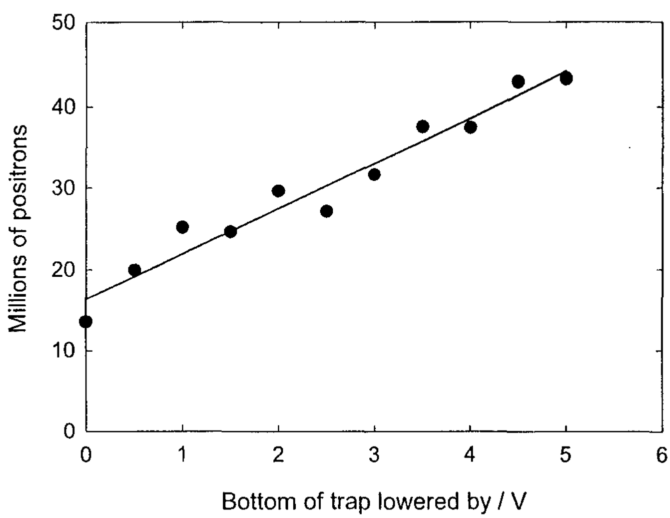

Figure 4. Effect on lifetime of lowering the bottom of the trap. Data shows the number of positrons left after 80 seconds of accumulation followed by 200 seconds of holding the positrons after the gas was pumped out. No rotating wall was used for these measurements. The line is a linear fit to the data with a slope of 5.7 million positrons per V.

fitted using a lifetime of 150 seconds, the main difference between the two sets of data being the increased number of positrons accumulated before the gas was pumped out when using the rotating wall. The data when the bottom of the trap was gradually lowered during accumulation exhibits an as yet unexplained slow linear fall-off up to about 200 seconds after which the data appears to follow an exponential fall off that again could be fitted with a 150 second lifetime.

To investigate this phenomenon further an experiment was performed looking at the number of positrons left in the trap after 80 seconds of accumulation without using a rotating wall and 200 seconds of holding without buffer gas as a function of how much the bottom of the trap was lowered during accumulation. This is shown in Figure 4 and reveals a linear dependence between the two quantities.

The rotating wall was optimised by mapping out the yield as a function of the frequency and amplitude of the applied rotating electric field. By yield we here mean the general effect it has on the plasma, both in increasing the total amount of positrons but also in centring them in the trap. The CsI diode detector monitored the total

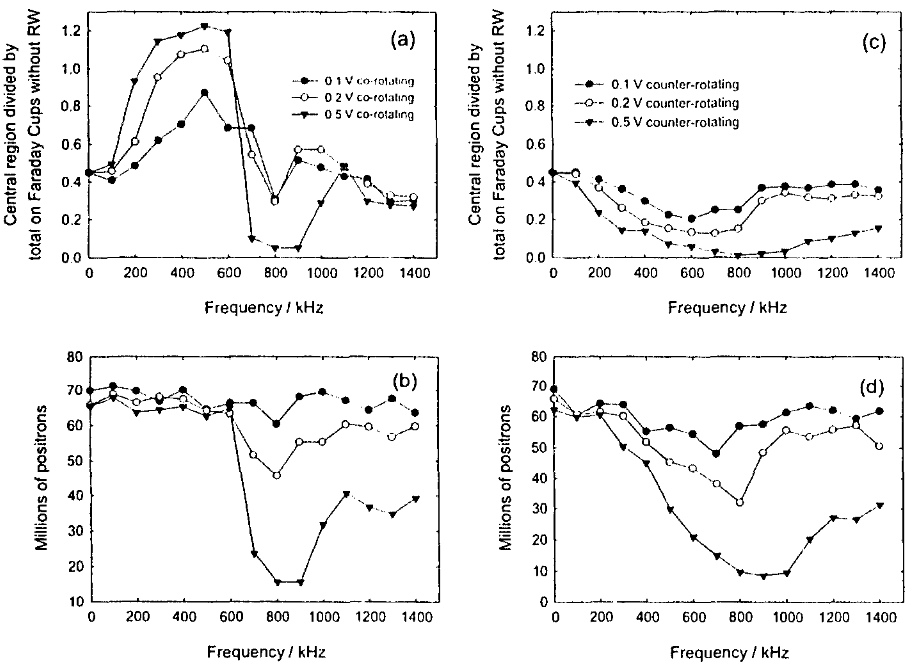

Figure 5. Optimisation of the rotating wall. (a) The number of positrons in the central region compared to the same number with no rotating wall. The data is for accumulation for 60 sec. and with the rotating wall on for the last 30 sec. of the accumulation. (b) CsI annihilation data for the same experiments. (a) and (b) are for a co-rotating electric field. (c) and (d) show the corresponding data for a counter-rotating field.

number of positrons while the segmented Faraday cup monitored the centering of the plasma. The centring could then be observed by looking at the increase in the signal on the central plates of the Faraday cup. Looking at various ratios between the the signals on the Faraday cup plates and fitting the data yielded information about positioning and absolute plasma sizes.

Figure 5 (a) and (c) show the ratio between the signal in a central region of the Faraday cup while using the rotating wall and the total signal on the Faraday cup with no rotating wall as a function of the applied frequency and amplitude of the rotating wall. The area of the central region constituted about 20 % of the total area of the Faraday cup. Figure 5 (b) and (d) show the total number of positrons for the same experiments as observed by the CsI diode detector. The data show how there appears to be a broad peak in the compression in the frequency range of 300-600 kHz and that the compression is increasing with increasing amplitude. Above 600 kHz there is an abrupt fall-off in the signal on the central plate coinciding with a quick drop-off in the total number of positrons. Note that up to 600 kHz the total number of positrons is very stable for all amplitudes and the fact that the ratio for the central region goes above unity must mean that parts of the positron plasma initially missed the Faraday cup altogether, but that the rotating wall has compressed even this outer lying part of the plasma into the central region. The data for the counter-rotating field ((c) and (d)) show a loss of positrons in the centre of the plasma coinciding with overall loss of positrons. The loss seem to increase with increasing amplitude of the rotating wall and also with increasing frequency, at least up to around 800-1000 kHz.

The data in Figure 5 seem to indicate a compression of a factor of about 2.5. However, the compression turns out to be even better than that. The central region of 20 % of the total area of the Faraday cups contains 5 individual plates. Of these only 3 were actually recording a signal when the rotating wall was being used. Unfortunately these 3 were not axisymmetric, meaning that the plasma was hitting the Faraday cup off-centre. This could possibly be attributed to the fact that our main magnet has had correction coils placed on the outside to make the field in the trapping regions sufficiently homogeneous and that these correction coils could probably induce a small dipole field at the end of the magnet. However, by looking at ratios between opposing plates and between central plates and the total on all plates and comparing this to similar data when the Faraday cup is moved slightly up or down (it is situated on a linear motion drive), it is possible to get absolute information about the position and size of the plasma. In this manner we found that the plasma had a FWHM of 15 mm when no rotating wall was being used and a FWHM of 3-4 mm when the rotating wall was being used. As the total number of positrons stayed constant or in some cases even increased this means that the central density increased by a factor of more than 10 and in quite a few cases even more than 20 when using the rotating wall. This compression ratio is much larger than that reported for N_2 previously [13] but this can possibly be attributed to the much larger pressures used. The pressure in the final stage of our trap, where the rotating wall electrode is situated, can be as high as a few times 10^{-6} mbar during accumulation. This is about two orders of magnitude higher than the pressure used in the earlier study [13].

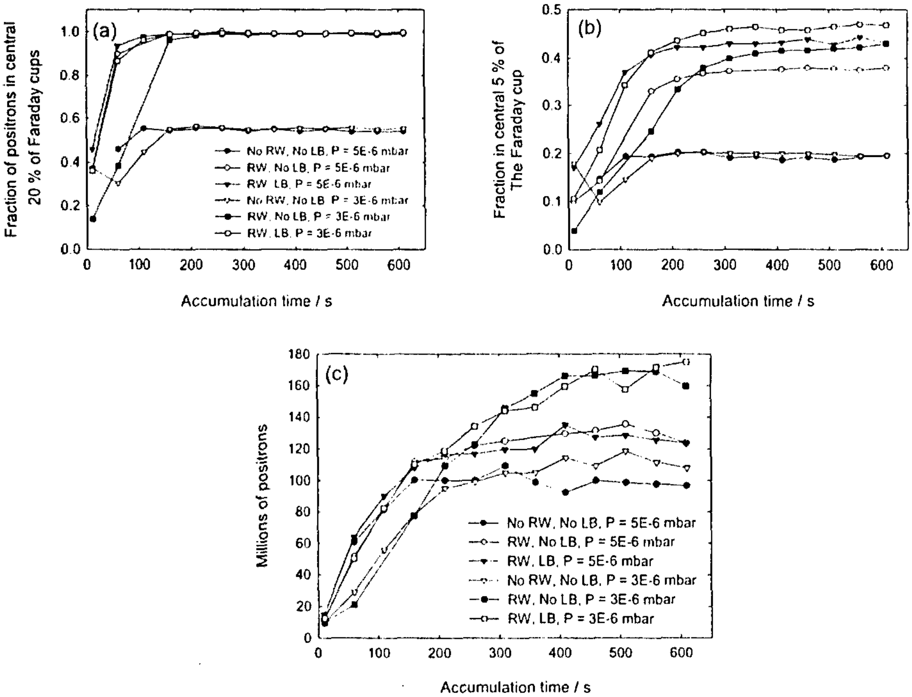

Figure 6. (a) The ratios of accumulated positrons within a central region constituting 20 % of the Faraday cups compared to the total on the Faraday cups. (b) A similar ratio for the central plate of the Faraday cup, constituting 5 % of the total area. (c) The number of accumulated positrons under the same conditions. Note how stable the ratios are for widely varying conditions. (RW = Rotating Wall, 500 kHz, 0.4 V; LB = Lowered Bottom of trap 4 V during accumulation).

One of the main features that made it possible to extract all this information from the ratios from the Faraday cup is that the signals from them were stable and reproducible. Figure 6 shows data of the ratio for the central 20 % of Faraday cup compared to the total (a) and for the single central plate constituting 5 % of the total area, again compared to the total signal on the Faraday cup (b) and the corresponding total positron numbers as observed by the CsI diode detector (c). The data contains 2 different accumulation pressures, with and without using the rotating wall and lowering of the bottom of the trap. It should be noted that the pressures mentioned are the pressures in the first pump-box before the electrode array. This pressure should have a direct linear relationship with the pressure inside the electrodes when in a steady state and is used for overall pressure stabilization.

The most remarkable thing about the data in Figure 6 is that the ratios are so reproducible even for very different total numbers of positrons and thus for very different densities. It would appear that if one can accumulate more than about 40-50 million positrons the plasma properties becomes very stable. This is obviously very important for the wider ATHENA experiment as it makes it possible to predict the size, density and position of the positron plasma prior to transferring it to the main ATHENA recombination trap. It has also made it possible within the last weeks to try to map the evolution of the plasma after the rotating wall is turned off and the buffer gas is pumped out. This is of importance to our experiment since it takes up to 20 seconds between beginning the gas pump-out and transferring the plasma. However, it is also of interest in order to try to understand how lowering of the bottom of the trap increases the lifetime of the plasma.

CONCLUDING REMARKS

The rapid progress recently in increasing the number of positrons trapped and the plasma density and characterization made possible by the upgrade of the positron source and the implementation of the rotating wall puts us a small step closer to making anti-hydrogen. Ongoing effort to transfer the positrons to the main recombination trap should allow us to deliver 100-150 million positrons to the ATHENA experiment every 5 minutes, the repetition rate being dictated by the cycle time for the pulsed transfer magnet. Optimising the transfer and recapture will be the main focus of our efforts over the next few months.

However, for the half of the year where there are no anti-protons available at CERN the Positron Accumulator could also act as a valuable reservoir of cold, well characterized pulses of low energy positrons for a variety of experiments making use of the traps and detection methods available at the ATHENA experiment.

ACKNOWLEDGEMENTS

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